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Results on Tau Physics from BABAR

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Recent results on tau physics from BABAR are reviewed. Limits on lepton-flavor violation in the tau decay process $\tau^- \to \ell^-\ell^+\ell^-$ are presented based on $91.6\,\mathrm{fb}^{-1}$ of data. In all six decay modes considered, the numbers of events found in data are compatible with the background expectations, and upper limits on the branching fractions are set in the range $(1-3)\times 10^{-7}$ at 90% CL. A preliminary measurement of the five prong branching fraction based on $110.7\,\mathrm{fb}^{-1}$ of data is presented with the result $\mathcal{B}(\tau^- \to 3h^- 2h^+ \nu_\tau) = (8.52 \pm 0.09 \pm 0.40) \times 10^{-4}$. A preliminary measurement of the tau lifetime based on $30\,\mathrm{fb}^{-1}$ of data is presented where a lifetime of $290.8 \pm 1.5 \pm 1.6$ fs is measured.

INTRODUCTION

The tau lepton is in many ways a laboratory in its own right. As the heaviest third generation lepton, it is a natural place to look for new physics arising at higher mass scales. It is also the only lepton which can decay to hadrons providing a unique environment to test QCD in both the first and second generations. This paper will review some recent BABAR results including a published search for Lepton-flavor violation (LFV) in the decay $\tau \to \ell\ell\ell$ [1], a preliminary measurement of the five-prong branching fraction [2], and a preliminary result on the tau lifetime.

The PEP-II storage ring, running at the $\Upsilon(4S)$ resonance, has performed very well and BABAR has recorded $244\,\mathrm{fb}^{-1}$ of data through July 2004. With an expected cross section for tau pairs at the PEP-II collision energy of $\sigma_{\tau\tau} = (0.89 \pm 0.02)$ nb [3], BABAR is also a tau factory, with almost 220 million $\tau^+\tau^-$ events recorded. The BABAR detector is described in detail elsewhere [4].

LEPTON FLAVOR VIOLATION

Lepton-flavor violation involving charged leptons has never been observed, and stringent experimental limits exist from muon branching fractions: $\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$ and $\mathcal{B}(\mu \to eee) < 1.0 \times 10^{-12}$ at 90% confidence level (CL) [5, 6]. Recent results from neutrino oscillation experiments [7] show that LFV does indeed occur, although the branching fractions expected in charged lepton decay due to neutrino mixing alone are probably no more than 10^{-14} [8].

Many extensions to the Standard Model (SM), particularly models seeking to describe neutrino mixing, predict enhanced LFV in tau decays over muon decays with branching fractions from 10^{-10} up to the current experimental limits [9]. Observation of LFV in tau decays would be a clear signature of non-SM physics, while improved limits will provide further constraints on theoretical models. Prior to the start of the B-factories, the best limits on LFV in tau decays came from CLEO: $\mathcal{B}(\tau \to \mu\gamma) < 1.1 \times 10^{-6}$ [10].

In this analysis, all possible lepton combinations consistent with charge conservation are considered, leading to six distinct decay modes ($e^-e^+e^-$, $\mu^+e^-e^-$, $\mu^-e^+e^-$, $e^+\mu^-\mu^-$, $e^-\mu^+\mu^-$, $\mu^-\mu^+\mu^-$) [11]. The signature of this process is three charged particles, each identified as either an electron or muon, with an invariant mass and energy equal to that of the parent tau lepton. Candidate signal events are required to have a "1-3 topology," where one tau decay yields three charged particles (3-prong), while the second tau decay yields one charged particle (1-prong).

Each of the charged particles found in the 3-prong hemisphere must be identified as either an electron or muon candidate. The particle identification (PID) requirements alone are not sufficient to suppress certain backgrounds, particularly those from higher-order radiative Bhabha and $\mu^+\mu^-$ events that can have four leptons in the final state, and additional selection criteria are applied to reduce these backgrounds.

Signal events are expected to have an invariant mass and total energy in the 3-prong hemisphere consistent with the neutrino-less decay of a tau lepton. The difference in reconstructed and expected energy (ΔE) and mass (ΔM) are calculated in the e^+e^- rest frame from the observed track momenta assuming the corresponding lepton masses for each decay mode. A LFV signal would peak at the origin in the $(\Delta M, \Delta E)$ plane, although detector resolution and radiative effects broaden the expected distribution. Rectangular signal regions are defined in this $(\Delta M, \Delta E)$ plane for each decay mode, and are shown along with observed data and expected signal distributions in Figure 1. To avoid bias, a blinded analysis procedure was adopted with the number of data

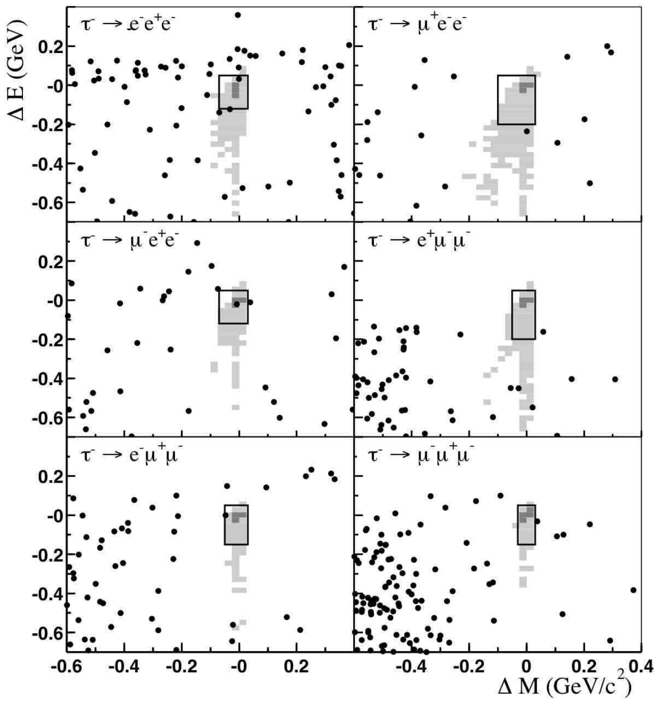

FIG. 1: Observed data shown as dots in the $(\Delta M, \Delta E)$ plane and the boundaries of the signal region for each decay mode. The dark and light shading indicates contours containing 50% and 90% of the selected MC signal events, respectively.

events in the signal region remaining unknown until the selection criteria were finalized and all cross checks were performed.

There are three main classes of background remaining after the selection criteria are applied: low multiplicity $q\overline{q}$ events (mainly continuum light-quark production), QED events (Bhabha and $\mu^+\mu^-$), and SM $\tau^+\tau^-$ events. These three background classes have distinctive distributions in the $(\Delta M, \Delta E)$ plane, and expected background rates are determined by fitting three PDFs, one for each background type, to the data observed in a grand sideband region shown as the area of Figure 1 excluding the signal region. The shape of these PDFs are determined from Monte Carlo (MC) samples or data control samples.

The primary systematic uncertainties involve the efficiency of the PID criteria and the uncertainties in determining the background fractions. The PID efficiencies are not estimated from MC samples, but rather are measured directly from data control samples. The background uncertainty is dominated by the statistical power of the data in the grand sideband region.

The numbers of events observed ($N_{\rm obs}$) and the background expectations ($N_{\rm bgd}$) are shown in Table I along with the signal efficiency and expected background rates in each final state. No significant excess found in any decay mode, and upper limits on the branching fractions are calculated according to $\mathcal{B}^{90}_{\rm UL} = N^{90}_{\rm UL}/(2\varepsilon\mathcal{L}\sigma_{\tau\tau})$, where

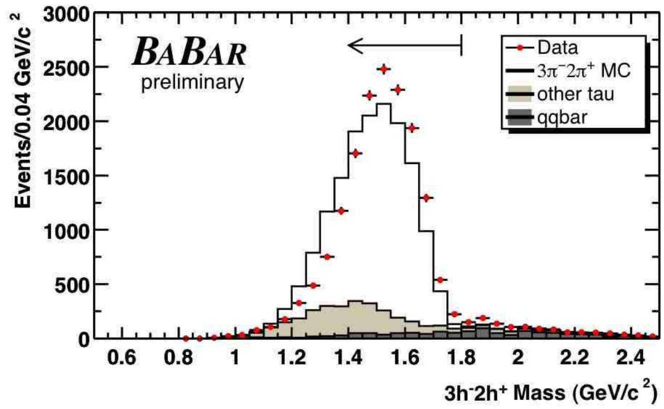

FIG. 2: Invariant mass distribution reconstructed in 5-prong tau decays compared to a phase space MC prediction.

$N^{90}_{\rm UL}$ is the 90% CL upper limit for the number of signal events when $N_{\rm obs}$ events are observed with $N_{\rm bgd}$ background events expected. The branching fraction upper limits have been calculated including all uncertainties using the technique of Cousins and Highland [12] following the implementation of Barlow [13].

The 90% CL upper limits on the $\tau^- \to \ell^-\ell^+\ell^-$ branching fractions, shown in Table I, are in the range $(1-3)\times 10^{-7}$. Belle has also produced similar results on a data sample of $87.1\,{\rm fb}^{-1}$ [14]. As both limits are statistically limited, these results can be directly combined taking into account relative luminosities, efficiencies, and backgrounds in each channels. The individual limits and combined results are shown in Table II. With the first data from the B-factories, these limits have been improved by an order of magnitude the level of 10^{-7}. With over $500\,{\rm fb}^{-1}$ expected from each machine in the next few years, and little background expected, these limits should approach 10^{-8} in the near future.

FIVE-PRONG TAU DECAYS

The semi-leptonic tau decay provides a particularly clean environment to study QCD and the hadronization process. With the large data sample available at *BABAR*, precision studies of hadronic structure can now be carried out in final states which were previously statistically limited. The previous best measurement of $\mathcal{B}(\tau^- \to 3h^-2h^+\nu_\tau)$ performed by CLEO was based on a sample of 295 signal events selected in $1.7\,{\rm fb}^{-1}$ of data [15]. In this analysis, a sample of nearly 15,869 events has been selected from a data sample of $110.7\,{\rm fb}^{-1}$.

Events are selected with a 1-5 topology, with an electron or muon tag on the one-prong hemisphere, additional requirements on the thrust, p_T, and missing energy in the event. Electron, π^0, and conversion candidates are not allowed in the signal hemisphere. No attempt has

TABLE I: Efficiency estimates, number of expected background events ($N_{\rm bgd}$), number of observed events ($N_{\rm obs}$), and branching fraction upper limits for each decay mode.

Mode	$e^-e^+e^-$	$\mu^+e^-e^-$	$\mu^-e^+e^-$	$e^+\mu^-\mu^-$	$e^-\mu^+\mu^-$	$\mu^-\mu^+\mu^-$
Eff. [%]	7.3 ± 0.2	11.6 ± 0.4	7.7 ± 0.3	9.8 ± 0.5	6.8 ± 0.4	6.7 ± 0.5
$q\overline{q}$ bg.	0.67	0.17	0.39	0.20	0.19	0.29
QED bg.	0.84	0.20	0.23	0.00	0.19	0.01
$\tau\tau$ bg.	0.00	0.01	0.00	0.01	0.01	0.01
$N_{\rm bgd}$	1.51 ± 0.11	0.37 ± 0.08	0.62 ± 0.10	0.21 ± 0.07	0.39 ± 0.08	0.31 ± 0.09
$N_{\rm obs}$	1	0	1	0	1	0
$\mathcal{B}^{90}_{\rm UL}$	2.0×10^{-7}	1.1×10^{-7}	2.7×10^{-7}	1.3×10^{-7}	3.3×10^{-7}	1.9×10^{-7}

TABLE II: Limits on LFV in $\tau^- \to \ell^-\ell^+\ell^-$ from *BABAR* and Belle ($\times 10^{-7}$ at 90% CL).

Mode	*BABAR* [1]	Belle [14]	Combined
$e^-e^+e^-$	2.0	3.5	1.5
$\mu^+e^-e^-$	1.1	2.0	0.6
$\mu^-e^+e^-$	2.7	1.9	1.2
$e^+\mu^-\mu^-$	1.3	2.0	0.7
$e^-\mu^+\mu^-$	3.3	2.0	1.4
$\mu^-\mu^+\mu^-$	1.9	2.0	0.8

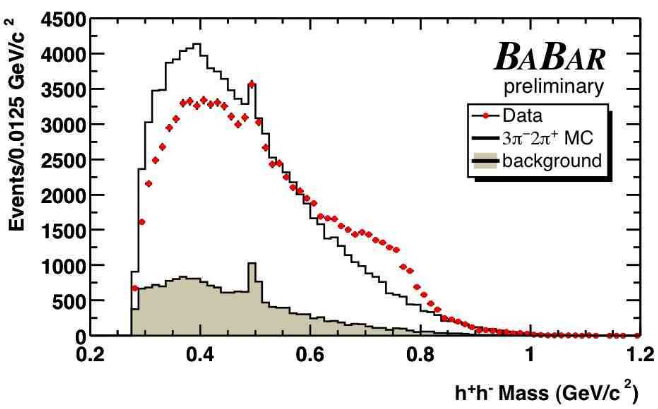

FIG. 3: Invariant mass of all opposite-signed pairs compared to a phase space MC predicton.

been made to classify hadrons as either pions or kaons. This selection achieves an efficiency of 7.5% with a purity of 79%. The majority of the backgrounds come from other tau decays with either five charged tracks and additional neutral pions, or tau decays involving K_s mesons. A preliminary branching fraction measurement of $\mathcal{B}(\tau^- \to 3h^-2h^+\nu_\tau) = (8.52 \pm 0.09 \pm 0.40) \times 10^{-4}$ is obtained which represents more than a factor of two improvement over the previous best measurement by CLEO.

Beyond the branching fraction, the large data sample allows a first detailed study of the hadronic structure in five-prong tau decays. Figure 2 shows the invariant mass distribution compared to a phase-space MC simulation provided by `Tauola` [16]. Clearly this simple model can not replicate the observed mass distribution. Figure 3 further shows the invariant mass of all opposite-signed pairs (six entries per event) again compared to the phase space model currently in `Tauola`. There is clear evidence in the data of ρ production, which while not surprising, is the first such observation in five-prong decays.

TAU LIFETIME

BABAR also has performed a measurement of the tau lepton lifetime. Again using the high statistics available, a very pure selection of 1-3 events is performed and the $r - \phi$ decay length is reconstructed from the primary interaction point and the 3-prong vertex. To reduce systematic uncertainties, the simple mean of the decay length distribution is used to extract the lifetime. A preliminary result based on $30\,{\rm fb}^{-1}$ finds a tau lifetime of $290.8 \pm 1.5 \pm 1.6$ fs, which is competitive with lifetime measurements performed at LEP.

CONCLUSIONS

First results from *BABAR* on tau physics have been presented with limits on LFV decays, hadronic structure, and the tau lifetime. This represents the start of a rich physics program made possible by the well understood detector and very large data sample available at *BABAR*. Additional new preliminary results including further LFV decay modes, more hadronic structure measurements, and an update of the lifetime will be made at the Tau04 workshop in September [17].

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